MICRO-EROSION METER MEASUREMENTS OF TRAVERTINE DEPOSITION RATES: A CASE STUDY FROM LOUIE CREEK, NORTHWEST QUEENSLAND, AUSTRALIA

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ABSTRACT

Although originally designed to measure surface denudation, the micro-erosion meter (MEM) can be adapted easily to measure deposition rates of chemical sediments such as travertines and speleothems. At Louie Creek, northwest Queensland, Australia, travertine deposition rates measured using the MEM average 4·15 mm a^{-1}. However, this figure masks considerable rate variability. Both purely hydraulic and hydraulically related variables appear to be the major mechanisms controlling deposition rates. The most rapid rates occur within relatively high-energy hydraulic regimes (impact and flow zones), whilst deposition rates in pools separating individual travertine barrages (standing water zones) are relatively slow. Deposition rate variations within spray and impact zones are related directly to discharge. The highest rates in flow zones correlate with the incorporation into the travertine of *in situ* and allochthonous biogenic material, such as caddis fly larvae, green algal mats and phytoclasts, which proliferate or are entrapped easily under such hydraulic conditions. Considerable spatial variability in deposition rates also prevails. The highest rates for a given set of hydraulic conditions occur at two sites, the Upper Everglades and the Lower Everglades. The MEM also measures net erosion of travertines. At Louie Creek, Most of the travertine erosion occurs in the wet season and is confined primarily to standing water zones. © 1997 John Wiley & Sons, Ltd.

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INTRODUCTION AND BACKGROUND

Travertine is a terrestrial calcareous sediment which is chemically or biologically precipitated from supersaturated waters of karstic, hydrothermal and/or artesian origin. The deposit can assume a variety of geomorphic forms depending largely on local topography and hydrogeology (Chafetz and Folk, 1984; Pedley, 1990; Pentecost and Viles, 1994). Travertine deposits may attain vast dimensions, as is evident from the extensive barrages at Plitvice, Croatia (Kempe and Emeis, 1985), and Antalya, Turkey (Burger, 1990). As a consequence, travertines are significant geomorphic features which may play an important role in regional hydrology and landscape development.

The physico-chemical mechanisms of travertine deposition are relatively well understood (e.g. White, 1988; Ford and Williams, 1989), and the extent of biological involvement in the precipitation of the constituent carbonate minerals is becoming increasingly appreciated (Pedley, 1992; Folk, 1993, 1994). However, relatively little is known about how rapidly travertine accumulates or why deposition rates vary within particular travertine-depositing environments.

The measurement of travertine deposition rates is important for several reasons. First, it addresses the fundamental geomorphic question of how fast particular landscape features develop. Secondly, modern rates may be compared with ancient rates; differences arising from such comparisons may indicate important

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changes in palaeoenvironmental parameters such as regional climate, discharge, sediment loads and stream chemistry. Finally, the detailed examination of deposition rates may expose significant spatial and temporal variations which equip researchers with a better understanding of the dynamics of travertine-depositing systems.

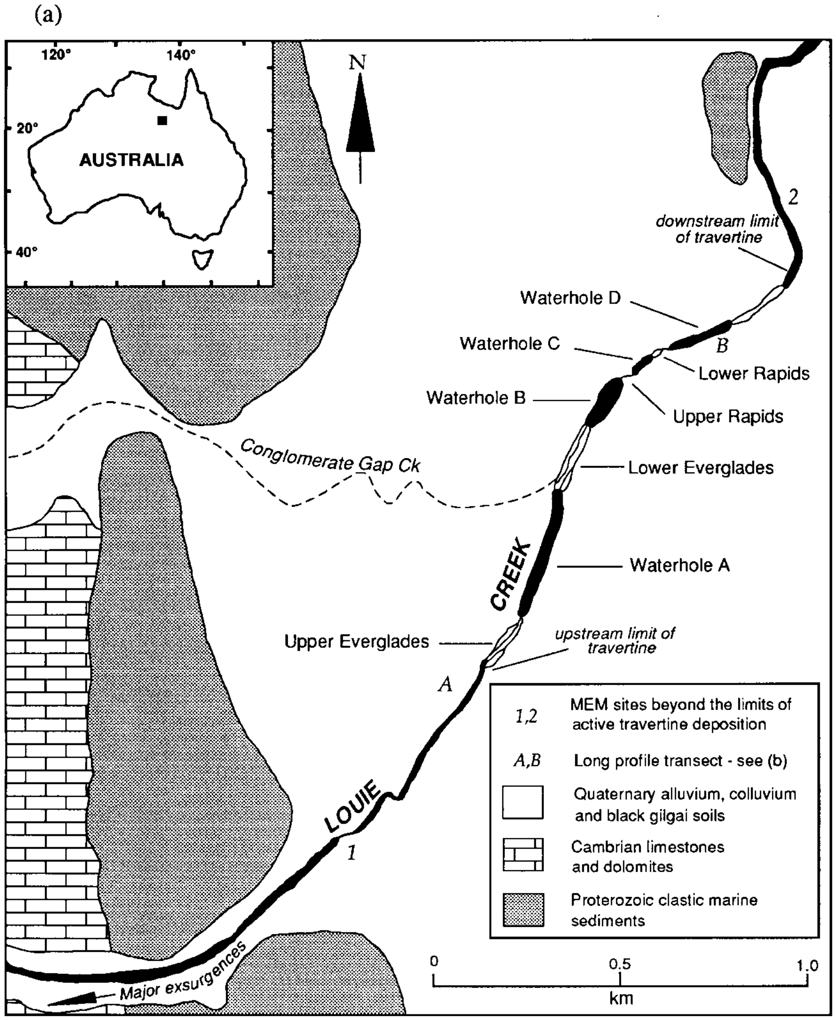
Compared with research on physico-chemical and biological aspects of travertine deposition, there is relatively little published work which deals specifically with rates of travertine deposition. Viles and Goudie (1990) summarized a selection of travertine deposition rate data and noted rates ranging from <1 mm a^{-1} to approximately 0·5 m a^{-1}. The highest rates appear to occur in hot-spring (or *thermogene*) travertines (*sensu* Pentecost and Viles, 1994), such as those from geothermal regions in Italy and the USA (Allen, 1934; Folk *et al*., 1985; Pentecost, 1994; Folk, 1994); Kitano (1963, cited in Folk *et al*., 1985), for example, noted rates of up to 1 m a^{-1} from hot-spring deposits in Japan. Rapid deposition of cool water (or *meteogene*) travertines (*sensu* Pentecost and Viles, 1994) seems to be more the exception than the rule (e.g. Pentecost, 1978, 1981), although Emig (1917) noted rates of up to 1 mm per month during summer months in an Oklahoma stream.

Most published estimates of deposition rates have been either inferred using mass balance models (e.g. Jacobson and Usdowski, 1975; Kempe and Emeis, 1985; Lorah and Herman, 1990) or derived from one of several possible direct methods of measurement. Mass balance models are input/output-based and use chemical and hydrological data to calculate net downstream losses of calcium carbonate. Such models represent an *indirect* means for determining deposition rates, since they produce values without physically measuring carbonate deposition. For example, Kempe and Emeis (1985) applied a mass balance model to travertine deposition Plitvice Lakes, Croatia, and concluded that 1×10^4 t a^{-1} of carbonate is deposited, which equates to 2 mm a^{-1} of solid carbonate spread over an area of 2 km^2. Whilst providing potentially useful overall estimates, such models generally rely on too few input data, make oversimplistic hydraulic assumptions and ignore seasonal and spatial hydrochemical input/output variations (Kempe and Emeis, 1985). In some cases, the results are inconsistent with rate determinations derived from potentially more precise means, such as the use of seed crystals (Lorah and Herman, 1990). In contrast, *direct* methods for estimating deposition rates involve the actual physical measurement of travertine growth. For example, Statham (1977) and Thorpe (1981) used accretion pins to directly measure deposition rates in Ireland. Biological activity has also been used successfully to directly measure travertine growth (Pentecost, 1987, 1989), particularly where such activity is confined seasonally and where associations between a particular organism and travertine fabric can be identified (e.g. Irion and Müller, 1968; Dürrenfeldt, 1978; Pentecost, 1987, 1989).

Whilst previous work on deposition rates provides valuable preliminary estimates of travertine accretion, no in depth and systematic attempt has been made to determine accumulation rates directly from the range of possible hydraulic situations. As a consequence, little is known about either the variation of accumulation rates in particular travertine systems or the controls on such variation. It is the aim of this paper, therefore, to report the results of a study of travertine deposition rates from a small karst stream in northwest Queensland, Australia. Rates were determined directly from over 50 artificial substrates which were positioned in the stream bed, retrieved periodically and measured using a micro-erosion meter (MEM). To the authors' knowledge, this is the first time the MEM has been used deliberately to measure accretion.

STUDY AREA

Louie Creek (18° 49′S, 138° 29′E) drains the northeast Barkly karst, one of Australia's largest karst areas (Figure 1). Its catchment is situated within the seasonally wet tropics, where rainfall is summer-dominant, highly variable and averages 535 mm a^{-1}. The creek is fed by numerous small springs and seepages which rise adjacent to the contact between Cambrian limestones and dolomites, and Proterozoic marine sandstones and conglomerates (Sweet and Hutton, 1982) (Figure 1a). Travertine deposition commences *c*. 1 km downstream from the point at which Louie Creek leaves the Barkly karst. These travertines, which may be classified as meteogene deposits, form a series of barrages (*senus* Pentecost and Viles, 1994) and pools over a distance of *c*. 1·5 km (Figure 1a). Individual barrages attain heights of over 2 m, although few are more than 0·5 m high. The modern travertine is flanked in places by extensive fossil travertines, some of which pre-date the Last Glacial Maximum (Drysdale and Head, 1994).



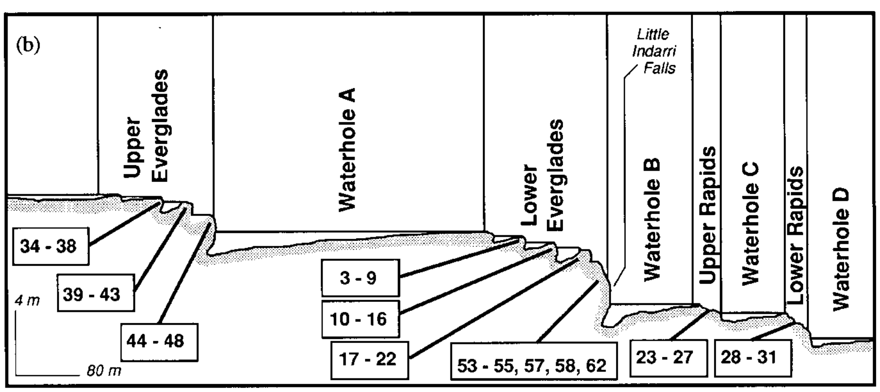


Figure 1. (a) The location and geology of the Louie Creek area. The limits of modern travertine deposition are shown, as are the locations of the four MEM tablets installed beyond these limits (see text for explanation). The Upper and Lower Rapids and the Upper and Lower Everglades are major morphological zones containing travertine barrages and small pools. Each of the waterholes is a long sediment-filled lake-like feature. (b) Schematic long profile of Louie Creek between points A and B in (a) showing the approximate installation point of each numbered MEM tablet. All but four tablets were positioned within the four major barrage/pool environments. Waterholes were excluded as measurement sites because of regular invasion by cattle

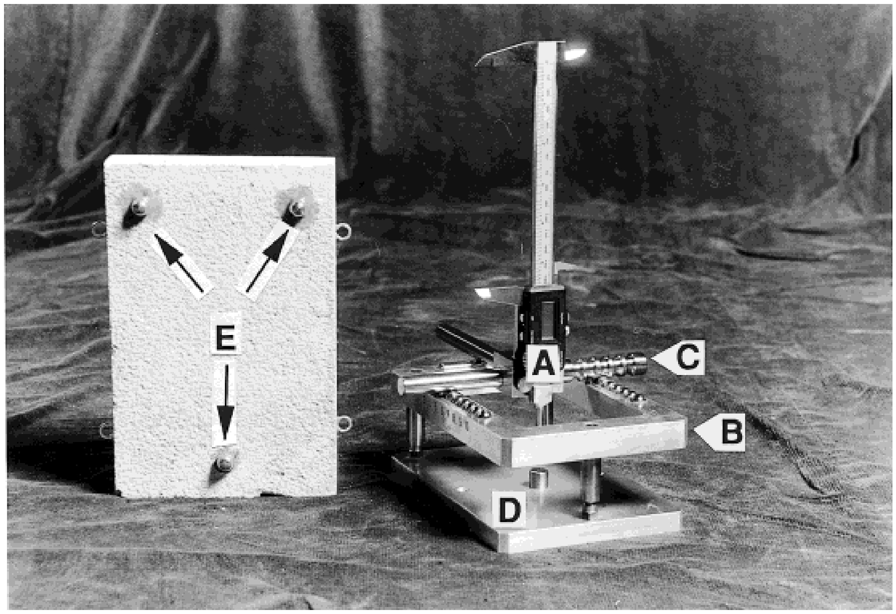


Figure 2. The MEM and a typical sandstone tablet used in this study. A, Probe with digital micrometer attachment; B, stage upon which the probe is mounted; C, bevelled t-bar for locating the probe at specific *x-y* datum points; D, datum plate for calibration; E, hemispherical studs upon which the stage (B) rests during measurement. A total of up to 50 datum points (5×10 points; short axis: A to E, long axis: 1 to 10) may be measured on each tablet, covering an area of 36 cm^2

METHODS

MEM configuration and tablet composition

Although designed originally to measure surface denudation (High and Hanna, 1970), the MEM can be used, with little modification, to measure chemical sediment accumulation. The method employed in this study is similar in principle to the limestone tablet MEM experiments of Spate *et al*. (1985). The instrument (Figure 2) is a slight variation on earlier traversing MEMs (Trudgill *et al*., 1981) and was designed to measure 50 data points per tablet on a 9 cm × 4 cm datum point grid.

Tablets composed of travertine should be the ideal substrate for the measurement of travertine deposition. However, at Louie Creek and elsewhere in the region, the rock is generally porous and brittle and therefore unsuitable for working. Given that travertine will accumulate on virtually any natural surface, a total of 54 tablets was manufactured from marine sandstone obtained from a quarry at Bundanoon, New South Wales. Each of the rectangular tablets had a surface area of 220 mm × 150 mm, was 30 mm thick and was fixed to the stream bed using either masonry bolts or tent pegs.

Installation and measurement of tablets

The tablets were installed during three field visits: June 1992 (12 tablets), October 1992 (36 tablets) and April 1993 (six tablets). Accumulation measurements were carried out during October 1992, April and October 1993, and April 1994. A week after initial installation, most tablets showed signs of colonization by aquatic insect larvae and microphyta and the hemispherical studs of the tablets (Figure 2) were coated with a thin carbonate film. The timing of installation of each batch of tablets meant that the first measurement period (or ‘colonization phase’) for June 1992 tablets (four months) was shorter than that for the remaining tablets (six months). Further, tablets installed in October 1992 coincided with a wet season whereas the first measurement period for both June 1992 and April 1993 tablets coincided with dry season conditions. However, neither of these inconsistencies was reflected in the colonization phase deposition rates.

The tablets were positioned at points along the creek (Figure 1b) according to the hydraulic classification scheme shown in Table I. Flow conditions along any reach of a travertine-depositing stream may be divided

Table I. The five hydraulic regimes identified in this study. The hydrological and other parameters indicated were measured prior to installation of October 1992 and April 1993 tablets as well as prior to subsequent measurements of all tablets

Hydraulic zone	*Description*	*Hydrological and other parameters measured**										
		1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*
Standing water (SWZ)	Water bodies of any depth whose flow velocity does not exceed $0{\cdot}01\,m\,s^{-1}$; confined to stagnant pools, impoundments associated with large travertine barrages and waterholes.	•	•	•	•							
Spray (SPZ)	Deflected water in the immediate vicinity of waterfalls and cascades; spray may range from a fine mist to an intense splash.	•	•			•						
Lap (LPZ)	Pulses of lapping water generated by plunge pool turbulence.	•	•		•		•	•				
Flow (FLZ)	Stream flow which is approximately normal to the cross-section moving at a velocity exceeding $0{\cdot}01\,m\,s^{-1}$; flow may occur at an inclination >0° and can include the passage of water down the steep face of a travertine barrage; includes seepage flow.	•	•						•	•	•	•
Impact (IMZ)	A column of water which becomes detached from the crest of a travertine barrage and strikes the substrate at the base of the barrage.	•	•							•		

* 1, Tablet inclination and declination; 2, foliage projective cover; 3, maximum and minimum water depth; 4, distance to point of nearest turbulence; 5, spray rate (the time in seconds for a Whatman 45 filter paper, held as close as possible above and parallel to the tablet measurement grid, to become completely saturated by the spray); 6, whether the tablet was completely submerged or partially exposed; 7, lap rate (the number of laps to wash over the tablet measurement grid per 50 seconds); 8, mean flow depth; 9, the mean of several instantaneous discharge measurements standardised to a flow width of 100 mm (FLZs) or to a cross sectional area of $100\,cm^2$ (IMZs); 10, the mean of several instantaneous flow velocity measurements; 11, presence or absence of *in situ* or detrital macroscopic biological material.

into a number of hydraulic subenvironments or regimes, of which five were recognized in this study: standing water zones, spray zones, lap zones, flow zones and impact zones (Figure 3). Each regime represents part of an energy continuum with standing water zones at the low-energy extreme and impact zones at the high-energy extreme. Given that the physico-chemical outgassing of carbon dioxide is potentially greatest where turbulence is more intensive, it might be expected that, for a specific reach of a travertine-depositing stream, carbonate deposition rates will be highest in impact and flow zones and least in standing water zones. All but four tablets were located within the reach of modern travertine deposition (Figure 1b); two were secured upstream and downstream of this reach (Figure 1a) with the aim of determining whether or not any accumulation occurred seasonally at these extremes. The six tablets installed in April 1993 were secured to the spillway of Little Indarri Falls, the terminal travertine barrage of the Lower Everglades (Figure 1b); three tablets were each positioned in a diverse range of spray and flow zone environments, with the aim of documenting accumulation rate variations *within* particular hydraulic regimes at a fixed point along the creek over a specific time period.

Prior to initial installation, each tablet was rinsed and air-dried in the field and a base measurement made using the MEM. Following initial installation and prior to each subsequent remeasurement, the hydraulic conditions to which each tablet was subjected were recorded (Table I). Tablets were removed from the stream bed and air-dried in the field under shaded conditions prior to remeasurement. Drying time varied according to surface composition, although the surface of each tablet was invariably visibly dry within four hours. Prior to and following the measurement of each tablet, the MEM was rezeroed using the instrument's datum plate (Figure 2). During each series of measurements for each tablet, repeat determinations were made at every tenth data point.

MEM performance and logistical problems

Spate *et al*. (1985) noted several critical error sources associated with the use of the MEM in erosion studies, particularly the problem of distinguishing natural surface lowering from that induced by instrument operation and/or operating conditions. However, during initial visits to Louie Creek, the rate of travertine deposition was visibly rapid, at least comparable in magnitude to rates of erosion recorded in soft limestones (e.g. Viles and Trudgill, 1984). Thus, the impact of the errors noted by Spate *et al*. (1985) is likely to be minimal in a travertine-depositing environment such as Louie Creek.

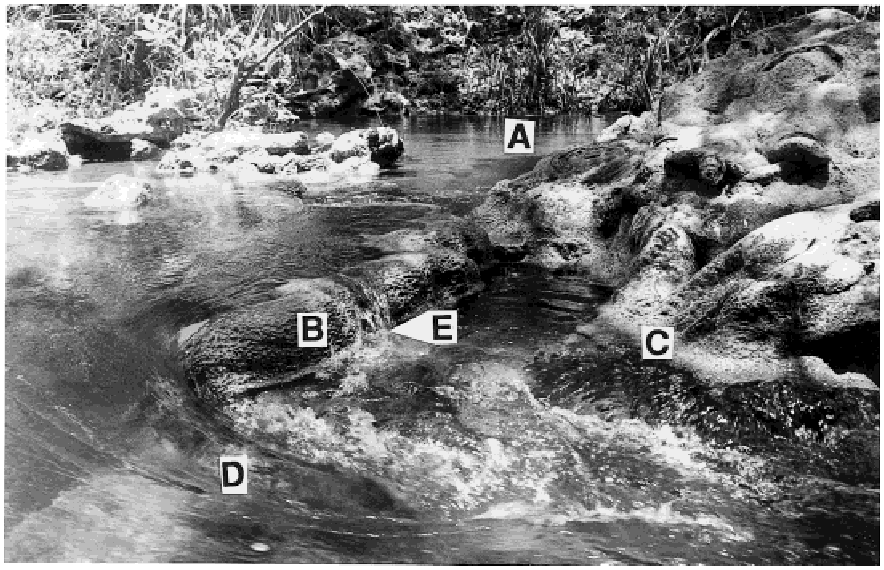


Figure 3. A small travertine environment in the Louie Creek region containing the five hydraulic regimes identified in this study: A, standing water zone; B, spray zone; C, lap zone; D, flow zone; E, impact zone

The most significant problem encountered at Louie Creek was the amount of compaction that occurs when the MEM probe first strikes the travertine surface. Compaction will yield results which underestimate accumulation; thus, all measurements must represent minima. Nevertheless, in the great majority of instances, the air-dried tablet surface was sufficiently hard and compact to withstand probe impact, and repeat measurements gave excellent replicability: the mean discrepancy from over 800 remeasurements was 0·01 mm. However, the travertine deposited on six tablets incorporated either thick spongy accumulations of Chlorophyta, root mats, abundant fragile phytoclasts or some combination of these. The relative softness of this material made MEM measurement difficult: on top of initial compaction by the probe, remeasurement errors of up to 0·53 mm were experienced. By the same token, these particular travertines accumulate very rapidly, and the remeasurement error in such cases only amounted to between 5 and 10 per cent of the annual accumulation rate, which is considered to be well within acceptable error limits.

Of the 54 tablets installed, a total of 37 was retrieved at the final measurement stage in April 1994. Two of these had accumulated so much travertine that, by April 1994, measurement with the MEM was not possible. Most of the tablets lost had been detached by wet season floods, including three of the four tablets installed at points outside the limits of travertine deposition. A total of 48 tablets was in place for at least one accumulation period.

RESULTS

Gross deposition rates

Gross deposition rates were derived from the 48 tablets (encompassing 2400 data points) which remained in place for at least one accumulation period. The mean and median rates were 4·15 mm a^{-1} and 2·53 mm a^{-1}, respectively. (Deposition rates may be expressed in terms of distance per unit time (mm a^{-1}) or as a mass per unit area per unit time (e.g. kg m^{-2} a^{-1}). The former option was preferred because of the enormous variations observed in travertine porosity and because land surface development is more readily conceptualized when distance quantities are used.) The highest recorded rate from any grid point was 30·36 mm a^{-1} whilst the lowest was –2·40 mm a^{-1}, one of several grid points which experienced net erosion during the entire experiment (over the entire duration of the experiment – the highest recorded deposition rate for any point between two consecutive measurements was just over 52 mm a^{-1}). The standard deviation of 4·84 mm a^{-1} reflects the considerable variation in deposition rates, a factor which would be obscured in studies employing mass balance models.

Table II. Mean annual travertine deposition rates (in $mm\,a^{-1}$) based on colonization phase data. Composite and individual tablet batch Mann–Whitney *U* test results are also shown.

Hydraulic zone	*June 1992*[*1]		*October 1992*[*2]		*April 1993*[*3]		*All*[*4]	
	Mean	*n*	*Mean*	*n*	*Mean*	*n*	*Mean*	*n*
SWZ	n.a.	n.a.	0·19	200	n.a.	n.a.	0·19	200
SPZ	0·67	100	2·39	150	0·86	100	1·46	350
LPZ	1·88	250	1·97	100	n.a.	n.a.	1·90	350
FLZ	2·28	250	2·42	250	10·01	150	4·38	600
IMZ	1·02	50	4·47	150	n.a.	n.a.	3·61	200

* One-tailed Mann–Whitney *U* test *z* scores indicate: 1, FLZ, LPZ > IMZ > SPZ; 2, IMZ > SPZ > FLZ, LPZ > SWZ; 3, FLZ > SPZ; 4, FLZ, IMZ, LPZ > SPZ > SWZ.
n is the number of datum points.

Inter-zonal variations in deposition rates

Introduction. Inter-zonal variations in travertine deposition rates may only be investigated using data from tablets which were subjected to 'hydraulically stable' conditions (i.e. they remained within the same hydraulic zone between two consecutive measurement episodes) for a given time period. This includes deposition rates derived from the colonization phase as well as those generated over a longer time interval. It is also possible to control for spatial variability in deposition rates by only considering data from tablets secured within the Upper and Lower Everglades, where most of the substrates were positioned.

Colonization phase data. The colonization phase is the time interval between the installation of each fresh tablet and the first post-installation measurement. Within this period, carbonate accretion commences and the tablet surface is colonized by aquatic insect larvae and microflora. According to the Wilcoxon signed-rank test (Siegel, 1956), the rate of deposition during the colonization phase is significantly lower than that of the second measurement period ($T = 155$; $p < 0{\cdot}01$; $n = 38$) and should therefore be considered separately.

A total of 34 Everglades tablets experienced stable hydraulic conditions during the colonization phase. As Table II shows, the colonization phase data indicate a considerable degree of hydraulic influence on deposition rates. The mean deposition rates derived from the June 1992 tablets increase from the spray zones through the lap zones to the flow zones. Thus, with the exception of the data for impact zones, which are based on one tablet with a low accumulation rate, there is a strong suggestion that deposition rates increase from zones of low energy to those of high energy. Data from the April 1993 tablets are restricted to only two zone types. Nevertheless, a clear difference is evident (Table II). The mean annual deposition rate recorded for flow zones is inflated by a very thick deposit of chlorophytic travertine which accumulated on one tablet. The mean and median rates for this tablet were 24·32 $mm\,a^{-1}$ and 24·12 $mm\,a^{-1}$, respectively; if data from this tablet are disregarded, the flow zone mean still exceeds the spray zone mean by a factor of three.

The data from the October 1992 tablets also suggest a trend of increasing rates towards the high-energy end of the hydraulic spectrum (Table II). The relatively high spray zone values are influenced largely by data from a single tablet which recorded mean and median deposition rates of 3·32 $mm\,a^{-1}$ and 2·83 $mm\,a^{-1}$, respectively. The mean rate from the remaining two spray zone tablets was 1·92 $mm\,a^{-1}$. Finally, when all colonization phase data are considered regardless of tablet batch installation date, a strong hydraulic trend is evident.

Statistical analysis using the Mann–Whitney *U* test (Siegel, 1956) confirms the significance of the above-mentioned hydraulic trends (Table II). Flow zone and/or impact zone rates rank the highest of each data set whilst standing water zone or spray zone data rank the lowest.

Longer-term data. Given that colonization phase deposition rates are generally slower than those generated during subsequent intervals, it follows that longer-term rates from tablets which were secured in place for 12 months will, other things being equal, bear the influence of the colonization phase more than rates from tablets which were in place for 18 months. Therefore, when examining hydraulic influences on longer-term deposition rates, it is important to ensure that comparisons are made between tablets which were installed at the same time and remained in place for the same duration. The tablets installed in October 1992 best meet these conditions.

From a total of 36 tablets installed in October 1992, 17 remained in place to at least October 1992 under hydraulically stable conditions. Of these, 14 remained in place under similar conditions for a further six months.

Table III. Mean annual travertine deposition rates (in mm a^{-1}) by hydraulic zone for tablets installed in October 1992. All tablets were subject to hydraulically stable conditions over three and/or two consecutive post-colonization phase accumulation periods

Hydraulic zone	*Two accumulation periods**		*Three accumulation periods**	
	Mean	*n*	*Mean*	*n*
SWZ	0·68	200	0·32	200
SPZ	2·62	50	4·03	50
LPZ	1·42	100	1·87	50
LPZ†	0·98	200	1·05	150
FLZ	4·69	300	8·30	250
FLZ†	4·33	350	n.a.	n.a.

* For both accumulation periods, one-tailed Mann–Whitney *U* test *z* scores show that FLZ > SPZ > LPZ > SWZ.
† Includes Lower Rapids data.
n is the number of datum points.

Table IV. Gross and periodic mean annual travertine deposition rates (in mm a^{-1}) from tablets which remained within flow and lap zones for at least three consecutive accumulation periods

Tablet number	*Gross mean deposition rate*	*Mean periodic deposition rates*			
		Jun 92 to Oct 92	*Oct 92 to Apr 93*	*Apr 93 to Oct 93*	*Oct 93 to Apr 94*
Flow zone tablets					
1	0·00	n.a.	0·00	0·00	0·00
19	1·76	1·44	1·44	3·36	0·64
36	4·35	n.a.	1·30*	5·28*	6·46*
34	4·67	n.a.	1·14	5·92*	6·94*
13	5·51	3·84*	8·52*	6·48*	(in LPZ)
15	5·86	n.a.	4·56*	6·12*	6·96*
10	6·56	1·68*	7·08*	5·64*	10·20*
42	8·80	n.a.	3·86*	7·54*	15·00*
47	9·69	n.a.	(damaged)	11·38*	8·00*
39	12·80	n.a.	0·82	4·58	33·00*
45	14·00	n.a.	0·52	14·42*	27·06*
Lap zone tablets					
31	0·60	n.a.	0·73	0·58	0·48
29	0·68	n.a.	0·51	0·31	1·23
26	0·77	n.a.	0·11	1·77	0·43
41	1·87	n.a.	1·59	1·16	2·85
4	3·15	1·54	4·42	5·97	0·14
3	3·97	1·79	1·55	6·72	5·12

* According to the Mann–Whitney *U* test, deposition rates on tablets with macroscopic biological material (i.e. phytoclasts, caddis fly larvae and/or root mats) present (*) ranked statistically higher than those on tablets without such material.

Hence, it is possible to examine hydraulic variations in deposition rates from two (12 months) and three (18 months) accumulation periods (Table III). This permits control over three key variables: hydraulic regime, and the timing and duration of travertine accumulation. A fourth variable, stream reach, can also be accounted for, since 12 of the 14 tablets with 18 months accumulation and 14 of the 17 tablets with 12 months accumulation were derived from the Upper and Lower Everglades (although the small number of tablets precludes comparison between these two sites). The remaining data are from the Lower Rapids.

As Table III shows, the general hydraulic trends evident in the colonization phase data persist in the longer term; indeed, these differences prevail for both 12 and 18 month periods. The Mann–Whitney *U* test shows that,

for both time intervals, flow zone rates rank higher than rates from all other zones, spray zone rates rank higher than rates in lap and standing water zones and lap zone rates exceed those of standing water zones (Table III).

Lower rates of accumulation at the Lower Rapids are also apparent in the data (Table III). The two lap zone tablets from the Lower Rapids recorded mean deposition rates of 0·41 mm a^{-1} and 0·66 mm a^{-1}, and 0·68 mm a^{-1} and 0·60 mm a^{-1} over 12 and 18 month periods, respectively. These values are considerably lower than the mean rates of deposition in the lap zones at the two Everglades sites, effectively reducing the overall lap zone mean value (Table III). The flow zone mean rates from the Lower Rapids (2·15 mm a^{-1}) similarly reduce the overall flow zone mean rate.

Intra-zonal variations in deposition rates

Introduction. The average deposition rate for each hydraulic zone conceals considerable variation *within* each zone. There are sufficient data from flow and lap zone tablets installed in June and October 1992 to attempt an explanation of such variation. Unfortunately, it is difficult to make similar comparisons with impact and spray zones because tablets situated within such zones are highly susceptible to critical changes in hydraulic conditions. Only one tablet from each of these two zones experienced long-term stable hydraulic conditions; data from these tablets are discussed below. Deposition rate variations also persisted in standing water zones. Since no clear patterns could be deduced from analysis of supplementary hydrological information for this zone (Table I), the data will not be considered further. Data from the April 1993 experiment will be discussed separately below.

Deposition rate variations on flow zone tablets. The range of gross mean deposition rates on flow zone tablets installed in June and October 1992 varied from just above zero to 14 mm a^{-1} (Table IV). Considerable deposition rate variation also occurred *between* individual measurement periods. For example, tablet 39 recorded a deposition rate of 4·58 mm a^{-1} for the period April–October 1993 compared with a rate of 33·00 mm a^{-1} for the period October 1993–April 1994. One possible explanation for such variation is changes in flow patterns over tablet surfaces. Changes in flow depth and velocity might be expected to influence deposition rates by facilitating or retarding outgassing. However, analysis of discharge data from flow zone tablets showed that no consistent hydraulic relationships emerged (Drysdale, 1995). The incidence of biological inclusions on tablet surfaces exerts a significant control over deposition rates (Table IV). Tablets exhibiting the highest periodic rates were statistically more likely to contain caddis fly larvae (order Trichoptera), root mats and/or phytoclasts on their surfaces than tablets recording lower rates.

The importance of caddis fly larvae to travertine formation has been discussed elsewhere (e.g. Thienemann, 1933; Dürrenfeldt, 1978; Drysdale 1993) and is highlighted in this study with reference to tablet 28 from the Lower Rapids (Figure 1b). Deposition on this tablet is largely composed of ridges of carbonate-encrusted retreats and nets of caddis fly larvae (Figure 4a) which greatly inflate the mean rate. The portions of the tablet surface free of caddis fly activity represent areas of ‘background’ travertine accumulation, where deposition is clearly occurring at a very slow rate. This pattern further supports the earlier observation that lower rates of travertine deposition occur at the Lower Rapids than at the two Everglades sites.

Deposition rate variations on lap zone tablets. Gross mean deposition rates on lap zone tablets ranged from 0·60 mm a^{-1} to 3·97 mm a^{-1} (Table IV); small standard deviations reflect the low variability in accretion across individual tablet surfaces. As with the flow zone date, the gross figures conceal some considerable periodic variations. For instance, tablet 4 recorded an overall rate of 3·15 mm a^{-1}: this incorporates rates of 5·97 mm a^{-1} between April and October 1993, and 0·14 mm a^{-1} between October 1993 and April 1994 (Table IV). During the latter period, erosion from the 1993–94 wet season floods removed much of the travertine accreted in the preceding period.

Variations in lap zone rates are difficult to explain. In some cases, tablets became submerged due to local or stream-wide hydrological changes, whilst other tablets remained exposed (i.e. the tablet surface intercepted the ‘lap range’). There is evidence that the variations in Table IV can be explained by the position of the tablets with respect to the water fluctuating surface. All of the Upper and Lower Rapids lap zone tablets were positioned in exposed locations. In each case, a distinctive raised band of more rapid accretion, which coincided with the lap range, was produced on the tablet surface. Two such bands were produced on tablet 26 (Figure 4b), representing the lap ranges for April to October 1993 (left-hand side) and October 1993 and April 1994 (right-hand side); the

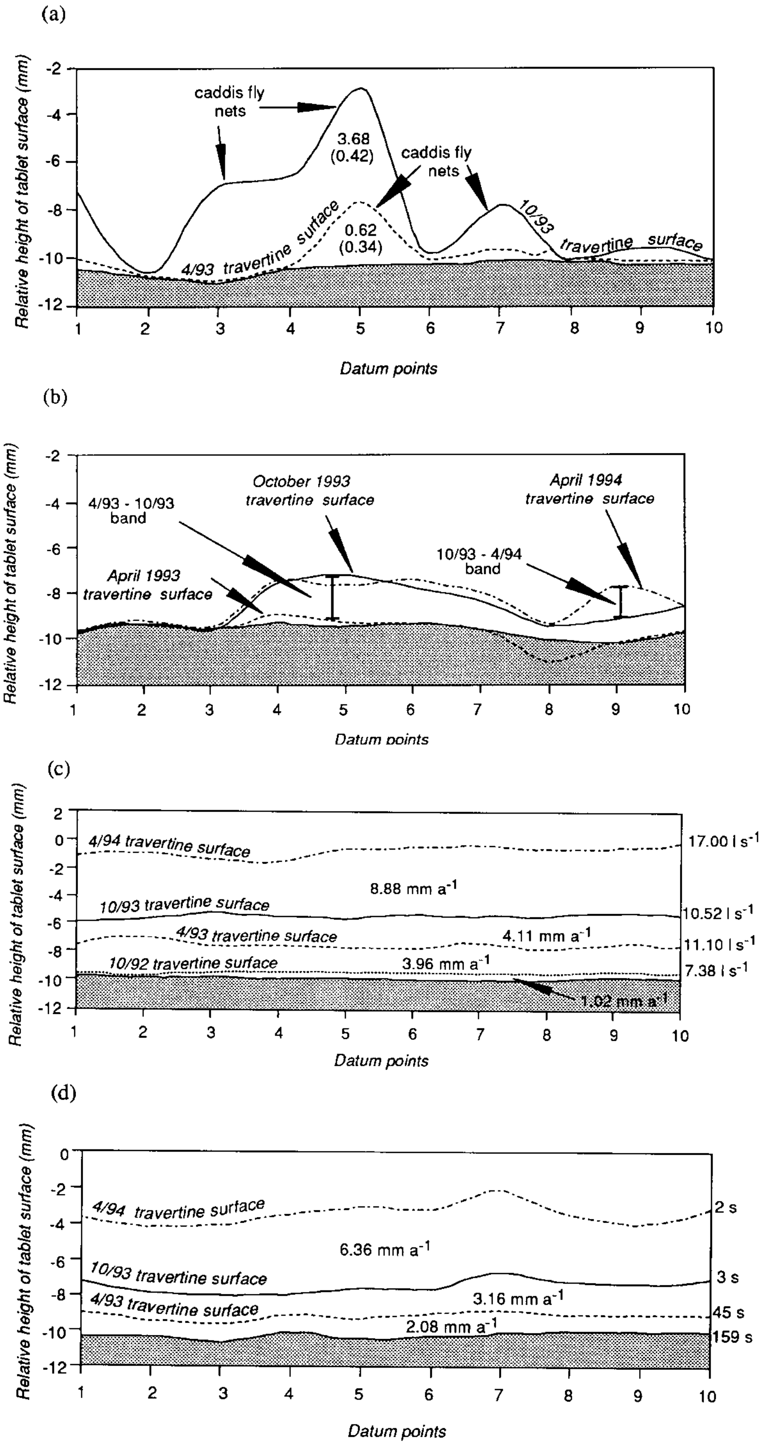


Figure 4. Cross-sections through selected tablets showing surface relief changes over time. (a) A long-axis cross-section from tablet 28 showing the relative relief produced by the nets and retreats of Trichoptera (caddis fly) larvae. Numbers are mean (and median) deposition rates (mm a^{-1}) for the periods October 1992–April 1993 and April–October 1993. (b) A long-axis cross-section from tablet 26 showing the lap zone bands which developed during the periods April–October 1993 and October 1993–April 1994. (c) and (d) Long-axis cross-sections through tablet 8 (c) and tablet 6 (d) showing periodic changes in deposition rates (mm a^{-1}) with changes in discharge (c) and spray rate (d). In (c), the values shown on the right-hand axis are discharges (l s^{-1}), whilst in (d) the values on the right-hand axis are spray rates (in seconds) (see Table I for explanation). In all cross-sections, the solid line above the shaded basal portion represents the original sandstone surface of the tablet; consecutive datum points are 1 cm apart

Table V. Gross and periodic mean annual travertine deposition rates (ADR in mm a^{-1}) and hydrological changes from tablets installed at Little Indarri Falls in April 1993

Tablet Number	*Zone type at installation*	*Mean ADR Apr 93 to Apr 94*	*At October 1993*					*At April 1994*				
			Zone type	*Mean of hydrological variables* Apr 93 to Oct 93*			*Mean ADR Apr 93 to Oct 93*	*Zone type*	*Mean of hydrological variables* Oct 93 to Apr 94*			*Mean ADR Oct 93 to Apr 94*
				d	*Q*	*s*			*d*	*Q*	*s*	
62	SPZ	0·66	SPZ	n.a.	n.a.	465	0·62	SPZ	n.a.	n.a.	503	0·70
57	SPZ	1·08	SPZ	n.a.	n.a.	197	1·08	SPZ	(tablet	was lost	in flood)	n.a.
58	FLZ	1·91	FLZ	33	1·065	n.a.	2·12	FLZ	30	1·672	n.a.	1·70
53	FLZ	2·54	FLZ	13	0·327	n.a.	3·58	FLZ	10	0·765	n.a.	1·50
54	SPZ	3·19	FLZ				12·46	SPZ	(changed	back to	FLZ)	–6·08
55	FLZ	18·09	FLZ	5	0·020	n.a.	24·32	FLZ	<5	<0·010	n.a.	11·84

* *d* (flow depth in mm), *Q* (discharge in $l s^{-1}$) and *s* (spray rate in seconds) represent the average of instantaneous measurements taken at each end of a given accumulation period. Mean hydrological data for tablet 54 are unavailable because this tablet experienced two episodes of hydraulic change.

migration of the band indicates a slight increase in water level and thus a vertical shift in the lap range at this stage. Relatively little travertine accumulated on the submerged zone at each measurement period on tablet 26. In contrast, accumulation rates over tablet 3, which was entirely submerged for the last three measurement periods, were far in excess of those which occurred within the lap range portions of tablet 26. This suggests that higher rates would have been experienced on tablet 3 had some or all of the measurement grid intercepted the lap range.

Deposition rate variations in impact and spray zones. Table 8 was the only substrate that was subject to sustained impact zone conditions. This tablet experienced deposition rates that appear to reflect variations in discharge (Figure 4c). Mean annual deposition rates between October 1992 and April 1993, and between April and October 1993, were virtually identical, as were the average discharges for these intervals. The discharge increase between October 1993 and April 1994 was a consequence of flow redistribution through a maze of travertine pools rather than a prolonged stream-wide increase in discharge; nevertheless, this increase corresponded with a greater than twofold rise in the mean deposition rate.

Tablet 6 was the only substrate that was subject to a continual spray (though of varying intensity) throughout the duration of the experiment. Figure 4d is a typical long-axis transect through the tablet, and shows the changes in periodic deposition rate with shifts in spray intensity. For instance, between April and October 1993, the spray rate (Table I) increased from *c.* 45 s to *c.* 3 s and the deposition rate was 3·16 mm a^{-1}. Over the following six months, an intense spray persisted. These conditions produced a mean travertine deposition rate of over 6 mm a^{-1}, suggesting that the rate of tavertine deposition increases with spray intensity.

Data from tablets installed in April 1993. The April 1993 experiment was conducted to document intra-zonal and inter-zonal variations in travertine deposition rates in spray and flow zones. One tablet (57) was lost during this experiment and only one tablet (54) experienced a change in hydraulic regime. The deposition rates suggest a strong hydraulic influence (Table V). With the exception of tablet 54, which experienced a shift from spray to flow then back to spray zone conditions, the overall mean rates were higher in flow zones than in spray zones. This trend prevailed for both measurement intervals.

In terms of intra-zonal variation, the mean deposition rates experienced by spray zone tablets during the colonization phase increase with spray intensity (Table I). For flow zones, deposition rates are inversely proportional to discharge (Table V). This latter finding is surprising, since more turbulent, higher-discharge conditions should enhance outgassing and, in turn, deposition rates. However, other factors appear to be important in this situation. Flow over the tablet recording the most rapid deposition (55) consisted largely of seepage waters. The lack of vegetation cover (and the consequent exposure to intense insolation) at Little Indarri Falls, coupled with the thin water films formed by the seepage flows, would enhance the loss of carbon dioxide from solution. This would promote rapid deposition rates. In addition, tablet 55 was colonized by a thick mat of green algae, which seem to favour seepage conditions. These microflora may also enhance carbonate precipitation via photosynthesis (see also Pentecost, 1984).

Table VI. Erosion of travertine from individual tablet datum points. Data have been broken down according to installation batch and season type

Tablet batch	*Number of eroded datum points*	*Number of tablets recording erosion*	*Percentage of each eroded tablet eroded*	*Percentage of all datum points eroded*
All dry season datum points	82	16 (34)	10·3	4·8
All wet season datum points	218	21 (45)	20·8	9·7
*1992–93 wet season**				
June 1992	19	3 (9)	12·7	4·2
*1993 dry season**				
June 1992	21	1 (8)	42·0	5·3
October 1992	61	15 (26)	8·1	4·7
1993–94 wet season				
June 1992	22	2 (8)	22·0	5·5
October 1992	139	12 (23)	23·2	12·1
April 1993	38	4 (5)	19·0	15·2
Colonization phase				
June 92 to October 92 dry season	8	2 (12)	8·0	1·3
October 92 to April 93 wet season	61	5 (29)	40·7	4·2
April 93 to October 93 dry season	0	0 (6)	0·0	0·0
Combined dry season	8	2 (18)	8·0	0·9

* Travertine erosion during colonization phase excluded.
Figures in parentheses represent the number of tablets included in the given category.

Travertine erosion

As well as measuring the net deposition of travertine, the MEM is also capable of recording net travertine erosion. It is thus possible to determine the time and extent of net travertine erosion and to examine whether certain hydraulic regimes and stream reaches are more prone to such erosion than others. Given the uncertainties of compaction by the MEM probe, only those points recording a net erosion rate of 0·20 mm a^{-1} were considered to reflect genuine travertine erosion.

Overall, net travertine erosion during the wet season (*c*. 10 per cent of all datum points) was twice that during the dry season (*c*. 5 per cent) (Table VI). This pattern persists to a large extent when the data are examined on a season-by-season basis: net erosion over the 1993–94 wet season was more prevalent than that during the preceding dry season, a finding that is supported by the colonization phase data (Table VI).

These gross figures, however, reveal little about the hydraulic conditions under which net travertine erosion occurs. Precisely half (109 of 218) the datum points eroded during either the 1992–93 or 1993–94 wet season were from tablets positioned in standing water zones. This reflects both the relative ease with which allochthonous particles trapped on the tablet surface are entrained by wet season flows, and the slow rate at which carbonate is precipitated *in situ* in such environments. Almost 20 per cent of eroded points were from lap zone environments, although the bulk of these was from a single tablet (4), which appears to have experienced severe erosion during the 1993–94 wet season floods.

Not all tablets experienced net travertine erosion. Of the 11 tablets which experienced zero erosion, eight were either from flow or impact zones or some combination of the two. This suggests that travertine in such zones accumulates so quickly that any erosion is masked by subsequent deposition. Further, all tablets positioned beyond the Everglades sites experienced some degree of erosion in both wet and dry seasons. By contrast, just under half the Everglades tablets experienced erosion under either wet or dry season conditions. The fact that all standing water zone tablets were positioned in the Everglades sites enhances this spatial trend.

DISCUSSION AND CONCLUSIONS

In the light of previous work, a greater range of travertine deposition rates occurs at Louie Creek than has been reported previously from other meteogene environments (Viles and Goudie, 1990). This reflects two key

factors. First, a hydraulic classification scheme was deliberately employed to determine variations across the entire hydraulic energy spectrum. Secondly, the tropical environment and persistent flow of Louie Creek ensures perennial, intensive biological activity, the products of which enhance travertine deposition rates considerably. The mean travertine deposition rate of 4·15 mm a^{-1} cannot be extrapolated to the entire travertine-forming reach of Louie Creek. Indeed, perhaps as much as 80–90 per cent of this reach could be classified hydraulically as standing water, where longer-term deposition rates have been shown to average only 0·36 mm a^{-1} (Drysdale, 1995). The overall rate of travertine deposition must therefore be considerably less than the mean figure obtained from the sites investigated here.

Hydrology exerts an important direct and indirect control on travertine deposition rates at Louie Creek. Colonization phase and longer-term data both suggest that deposition rates increase along a gradient of increasing hydraulic energy, with the lowest rates occurring in standing water zones and the highest rates confined generally to flow and impact zones. Rates within the spray and lap zones lie somewhere between these extremes. Superimposed on the hydraulic controls is a spatial pattern: both the longer-term and the colonization phase data indicate that the highest deposition rates occur within the Upper and Lower Everglades. Compared with the Upper and Lower Rapids, the travertines at the Everglades sites are more extensive and form larger geomorphic features. Turbulence and thus outgassing is more vigorous and sustained, conditions which theoretically favour greater carbonate precipitation from a bulk solution of a given level of supersaturation. The processes at the Everglades sites are therefore self-reinforcing.

Considerable intra-zonal variation in deposition rates also prevails. Within flow zones, the highest rates occur under two contrasting sets of conditions: with the inclusion of macroscopic biological material under fully turbulent flow conditions, and with the growth of thick masses of green algae in areas with high insolation and shallow seepage flow. Under turbulent flow conditions, caddis fly larvae thrive and phytoclastic material is transported then entrapped, especially at dam crests. Enhanced physical release of carbon dioxide is likely from these waters and may be critical in rapidly cementing entrapped material to the stream bed. Such entrapment would also increase surface roughness, which in turn increases the ability of surfaces to further impede the passage of debris in the water column. Under seepage flow conditions, equilibration between the stream waters and the atmosphere with respect to carbon dioxide would be assisted not only by the thickness of the water film, but also by warming. In short, some of the highest rates of travertine deposition in Louie Creek are not simply a function of physico-chemical processes *per se* but are due to the propensity for biological material to colonize or otherwise become entrapped on travertine surfaces under specific hydraulic conditions.

Although deposition rate variability within impact and spray zones could only be evaluated from single tablets, the available data suggest that rates increase with discharge, probably in response to progressively more vigorous carbon dioxide outgassing. Impact zone conditions seem to be too harsh to support colonies of caddis fly larvae and too turbulent for the entrapment of phytoclasts, especially where discharges over a tablet surface are relatively high (>5 1 s^{-1}). The results from tablet 8 thus provide valuable data on rates of travertine deposition in the absence of macroscopic biological material since they represent the deposition of near-pure calcium carbonate.

Deposition rate variations within lap zones appear to be a function of whether or not the measurement grid intercepts the lap range in a particular lap regime. Results from this study suggest that deposition rates are greater within the lap range than in the permanently submerged zone. Both physico-chemical and biological mechanisms may be responsible for the higher deposition rates in the lap range. Thin films of water are cast over the exposed tablet surface during the lapping process. The rate of carbon dioxide diffusion to the atmosphere from these films would be more rapid compared with that from the adjoining body of water. This would assist the physico-chemical process of carbonate precipitation. In addition, thin sections of travertines sampled from lap (and spray) zones show a dominance of filamentous cyanobacteria colonies possessing a distinctive upright growth habit (Drysdale, 1995). Such a habit appears to induce more rapid carbonate precipitation along a plane normal to the substrate. This would lead to deposits of travertine thicker than would be the case if the colonies were to possess a lateral growth habit. Upright microbial colonies may only grow vigorously where specific hydraulic conditions permit, although further investigation is required to confirm this hypothesis.

The MEM data also reveal evidence of net travertine erosion. The results indicate that net travertine erosion is most widespread during the wet season, in standing water and lap zones and the least in flow and impact

zones, and at the Upper and Lower Rapids.

Tavertine deposition rates at Louie Creek exhibit considerable spatial and temporal variability. The MEM is a simple but potentially very effective means of identifying and quantifying such variability, which would otherwise go undetected using indirect techniques such as mass balance models.

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